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EXPLORING EUROPA'S OCEAN: A CHALLENGE FOR MARINE TECHNOLOGY OF THIS CENTURY

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ABSTRACT
The Galileo spacecraft has sent back tantalizing image data hinting at a vast ocean beneath a thick ice crust on Europa, one of Jupiter's moons which is about the size of our moon. NASA plans to establish definitively whether this ocean exists with the Europa Orbiter mission to be launched in 2003. Should the Europa ocean be a reality, and this looks quite likely, it will mean that another planet besides Earth has an old, deep, salty ocean; the consequences of such an ocean are profound, and there are good reasons to be prepared to take the next step, an in-situ examination of this ocean. A deep subsurface in-situ study of another planetary body has never been attempted, and the challenges are considerable. In this paper we address the technology to be developed to be ready for this exciting mission, and we seek to initiate the exchanges needed between the marine technology and space exploration communities.

1. BACKGROUND

For the past two years the NASA spacecraft Galileo has been acquiring from Europa, a moon of Jupiter, image and geophysical data that have profoundly changed our view of that icy world, and, in the process, our perceptions of Earth itself. These data sets provide strong evidence that Europa had, and may have even today, an immense ocean of liquid, salty water, an ocean that may contain more water than Earth's oceans. In the outer solar system we have long known about icy planets and moons, but Earth was always "The Ocean Planet" as Jacques Costeau was fond of saying; now we simply live on one of the ocean planets. Additional data indicate that Callisto, another of Jupiter's moons, may also have a liquid ocean. In summary, these cold distant moons, circling Jupiter like a small "solar" system, may have large, deep, cold, salty, old oceans. The consequences of such oceans being present are not yet examined, but the intrinsic interest in exploring them is clear.

2. THE GALILEO DATA

Galileo collected three kinds of data that are significant in this discussion: image, gravity, and magnetic. These are all data types that Earth scientists, oceanographers in fact, are familiar with (for Galileo data go to http://www.jpl.nasa.gov/galileo/images.html). The gravity data (Anderson et al, 1998) tell us that the outer, low-density layer of Europa, the layer once taken to be water ice, is thicker than earlier thought; the best estimates now are that the outer layer of water and ice is about 150 km thick (with a suite of possibilities ranging from 125 km to 300 km, depending on internal structure). The magnetic data suggest an induced field from a salty, liquid ocean of a comparable depth (Khurana et al, 1999). The most intriguing Galileo data, however, come from the imaging system. These data suggest an icy surface of recent formation characterized by several dynamical processes and containing salts possibly derived from the subsurface ocean (McCord et al, 1998).

Figure 1 shows the range of interior structures that have been suggested for Europa. The Galileo gravity data indicate a low-density outer layer about 100 km thick (Anderson et al, 1998), confirmed by spectral data to be mostly water ice; the image data suggest that the ice may be only a few kilometers thick, but they also show dimple features suggestive of the presence of solid-state convection in the form of diapirs. Finally the magnetic data indicate a conductor approximately 100 km beneath the surface (Khurana et al, 1998); this conductor is probably a salty ocean but could even be a metallic layer 30 m thick. Figure 2 shows image data of a "Chaos" region. To anyone who has worked in ice-covered seas, this image speaks of ice floes floating in brash ice (see e.g. Drinkwater, 1989), and the freeboard and random attitude of the ice blocks further suggests floating ice. Another, analogy can be found in deformational processes of Antarctic ice shelves (Swithinbank, 1988). Thus a "consensus" crossection of Europa would involve a combination of the cartoons of Figure 1; an ice cover 2-10 km thick with a thin, cold skin and a warmer convecting layer, underlain by liquid water.

3. SCIENTIFIC CONSIDERATIONS

The profound issue brought up by the Europa ocean is that of its possible life, although the properties and dynamics of a large, tidally driven, lifeless ocean are doubtless also interesting. No other site in the solar system has liquid water in the quantity and age speculated for Europa. There are conventionally recognized requirements for life, and these become observational requirements for a mission to the Europa ocean. First and foremost there is a need for a source of (chemical) energy, a source that would remain available for billions of years, without recourse to the sun. While tidal and geothermal sources can be imagined, energy for life is more constrained that the energy to maintain a liquid ocean, as has been discussed by Gaidos et al, 1999 who argue that the life on Europa would be at best microbial. On Earth, viable microbial life has been noted preserved in ice sheets (Abyzov et al, 1998) and respiring in glacial environments which are sharply limited in available energy (Sharp et al, 1999). In Earth's past, subglacial processes have been significant in the survival of life through periods of heavy ice cover (Hoffman et al, 1998).

In general in the search for life a complex of properties must characterize the prospective organisms:
1. The organisms utilize energy from the environment for reproduction, maintenance and other functions.
2. The organisms will produce a departure from equilibrium conditions in their environment, certainly locally and possibly globally
3. The organisms will be characterized by structure reflective of function; at a minimum there will be a surface separating the organism from its environment.
All of these properties are measurable in a theoretical sense, although the actual instrumentation to accomplish such a measurement is not necessarily obvious, and herein lies the art of the science. We must settle on a comprehensive, simple, robust set of measurements that will result in a highly confident determination concerning life in the Europa ocean, a challenging task, very similar to issues the academic community has grappled with in past, with mixed success.

In the specification of probable science objectives it is useful to partition them into those related to habitat description and those that are specifically aimed at organisms. The first consideration is to obey the stricture "Know your planet," in response to lessons learned from Viking lander data taken on Mars. In effect it reminds us that life must have properties and perform functions consistent with its habitat, and life detection experiments must be designed consistent with the nature of that habitat. Thus, even if the life detection experiment fails, good data on the environment permit a more refined follow-on study. This type of data includes basic description information such as variations in pH, pE, salinity, turbidity, temperature, chemical stratification, inorganic composition, organic constituents and molecular size distribution, isotopic abundances, and the like. These measurements are typically not that demanding, in principle, although, for some, sophisticated instrumentation is required. Actual life detection science can take a number of avenues, all relying on rather complex instrumentation, none of which has been tested. We have no case studies resulting in successful determination of life, and the Mars Viking studies and Mars meteoritic studies were noisily ambiguous. This is still an open issue.

4. A EUROPA MISSION PROFILE AND ROADMAP

A mission is now approved for the Europa Orbiter to be launched in 2003. The goals of the orbiter are 1. To verify the ocean or its absence, 2. To develop information on the ice thickness, and 3. To generate information on landing sites for future missions. Data from this mission will be available in 2007 and 2008; a sufficiently exciting result could drive an immediate follow-on mission. The follow-on in-situ mission to the Europa ocean would then have a technology freeze in about 2010 and a launch in about 2012 for arrival at Europa in 2016 and entry to its ocean a few months later. Thus, there is a 10-year timespan to examine technology requirements and to develop and test solutions. It is possible that NASA can be convinced to address these technologies in view of the importance of the information from deep below the surface of Europa, and such a commitment is a key first step. As of this time we need an updated NASA roadmap for this technology development; that is, specific marching orders for the required developments. We must develop this roadmap in collaboration with the scientific and operational communities that have relevant experience working on Earth. For working in the deep, dark, cold ocean of Europa, the marine technology community has the most to offer the Europa Ocean Mission. This note seeks to initiate the exchange needed between the marine technologists and the space community.

5. MISSION REQUIREMENTS

Transportation into the Europa ocean and communication of data back to Earth is an exceedingly challenging prospect. A part of that challenge lies in the Europa ocean itself, and additional elements are at the surface, in the ice cover, and in the geometrical relationship of Europa and Earth. In general the crucial scientific objective is to determine if the Europa ocean supports life, and there will be secondary objectives, all to be settled on later, relating to the physical and chemical states of the ocean and ice cover.

6. SCIENTIFIC AND OPERATIONAL AUTONOMY

Several factors in Europa ocean exploration call for scientific autonomy: reduced data transfer rates from subsurface sites (presumably to surface systems linked to Earth), higher communication latency due to irregular contact between Earth and Jovian satellites, environmental uncertainty and variability such that the events affecting the exploration probe in the ice and ocean are unpredictable, sensors with varied data and control requirements, complexity of mission, and the mix instrument application scenarios such that some instruments are only put into action when other data sets warrant specialized data. Scientific autonomy is crucial to mission success and operational autonomy is crucial to mission survival, and the two are not independent. Autonomy is an integral aspect, not a feature. The autonomous system, relying on carefully installed mission objectives, capabilities, and constraints, will control the robotic system progress, command observational systems, determine and conduct communications, analyze data from scientific and control sensors, undertake protective actions, and maintain knowledge of the status of mission and system.

Autonomy is not a new topic in marine technology, and autonomous systems play an ever-increasing role in maintenance, installation, monitoring, and environmental assessment in marine activities. Some of the Europa ocean autonomy procedures will be drawn from procedures for work in Earth's ocean, removed a few large steps in the distance to Europa and the thickness of the overlying ice.

7. PLANETARY PROTECTION

Planetary protection is the quantifiable and specific avoidance of contamination of another planetary site or the Earth as the consequence of exploration. At present planetary protection technology available for Europa exploration, or its equivalent, is rather primitive when contrasted with the expectations implicit in its applications in the next decade; these are shown graphically in Figure 3. The public and the general scientific community fully expect that future planetary explorations will be conducted carrying not even so much as a strand of genetic material from Earth, while the biological technologists practice sterilization in terms of a few orders of magnitude reduction in microbial density. To date they are not speaking the same language. Explorations to extraterrestrial sites characterized by ice, water, and mineralogic material are a worst case for meeting anticipated planetary protection requirements yet these same places are the ideal locales in which one would search for life, a central task of the NASA space program.

Planetary protection research is continuing to develop and adapt methods for quantifying and characterizing microbial populations on space hardware, and comparative studies for cleaning hardware to reduce bioburden are also underway. Standard techniques for assessing bioburden today include:
- NASA standard cell culture bioassay based on colony forming units
- Epifluorescence microscopy for direct enumeration of microbial populations
- PCR-based detection of microbial ribosomal DNA

New techniques are under examination including more advanced UV fluorescent approaches to cell and spore observations.

Planetary protection issues impact other aspects of design and operation. Material selection is constrained by the requirement of sterilizability; instruments will probably have to be selected such that they can be bathed in sterilizing solutions without suffering degradation, etc. Clearly the technology of contamination avoidance and its verification is in need of immediate attention, and this is an area in which the recognized experts are a considerable distance from the solution.

8. COMMUNICATIONS

Galileo images of Europa show signs of fracturing and upwelling of material similar to that experienced in the sea ice pack and ice shelves of Earth. Ice ridges and lateral cracks caused by tidal deformation (Hoppa et al, 1999) and other forces not only suggest on-going dynamics but also suggest an ice crust of a few kilometers thickness. Interpretation of the Galileo data will continue to enrich our understanding of the Europa ice environment. However, in the absence of quantitative information, it is clear that to develop a mission to accomplish a deep penetration of the crust, we must be conservative in our assumptions about the dynamics and composition of the ice environment. Based on the above, and recognizing that deep penetration equates to approximately 10 kilometers of range, tether based communication between the surface lander and the exploration vehicle is not a reliable approach. To assure survival within mass limitation, feasibility analysis identified ice transceiver relays as the current baseline for communication between the exploration vehicle and surface lander. Given this conclusion, the real problem to be addressed is developing a miniature transmit/receive device which fits in a limited volume and transmits with sufficient power and bandwidth to communicate through kilometers of ice containing fractures and impurities which attenuate the signal.

The baseline approach to communication is to deploy microwave repeaters in the ice which will relay data to the surface lander. The exploration vehicle transmitter, in this design, will be attached to an anchor which remains in the ice near the water surface and is cabled to the vehicle. The design calls for a number of small ice transceivers (ea. approximately 2-3 cm thick by 10 cm in diameter) which are released from the rear of the probe with spacing between transceivers based on a sampling of signal strength, ice temperature and conductivity. When the ice character and corresponding signal strength of the last deployed transceiver suggest that an optimal signal amplitude and error threshold has been reached, the next transceiver in the stack is released. The analysis suggest that the projected 100-120 mw transmit signal power, coupled with use of either a 10 cm antenna patch array or quad dipole antenna, will allow a 10 Kb/sec signal to be relayed several hundred meters in ice containing 13 ppm salt impurities. This analysis shows that the problem of communication is appreciable and that the design level is quite preliminary, but there is reason to believe that this job can be done.

It is of course possible that a UHF link is capable of supporting sufficient data rate even in the presence of attenuating constituents in the ice. This solution would rely on the technology developed for communications with submarines, but with shorter wavelength and much reduced power.

9. INSTRUMENTATION AND DATA SYSTEMS

A selection of scientific payload will be made by review of proposals that define the Europa ocean exploration mission, but we list here a strawman suite of instruments designed to accomplish probable scientific objectives and also meet the qualifications of availability, reliability, interpretability, and deployability. This list is thus conservative, and we recognize that a planetary mission will have instruments of greater sophistication, and that microinstrumentation is a field that is changing with exceptional speed. The scientific data would be acquired from instruments designed to manage the vehicle, describe the habitat being visited, and detect life. At this point a list might be:

9.1 Control Sensors. Although these sensors are installed for physical management of the vehicle, their data may be useful to science. These include temperatures of various components, system attitude, signal strengths for communications systems, and the like. It is highly probable that a camera will be part of the operational instrument suite.

9.2 Habitat Sensors. These sensors describe the water, ice, and mineralogy in general terms of conductivity, pH, temperature, and electrochemical spectra. The instruments can be characterized by simplicity of design and deployment (no plumbing is required; the sensors are in the melt-water around the exploration vehicle).

9.3 Optical Sensor Systems. These sensors encompass control, habitat analysis, and life detection; they are the consequence of the human tendency to rely on visual information. At this point in the Europa exploration concept development we anticipate one or more cameras recording the nature of the environment, turbidity sensors, UV spectrofluorometers and Raman spectrometers, and certain simple optically-based analytical tools such as dissolved oxygen chromophore systems.

9.4 Sampling Systems.. Quantitative information on such chemical variables as carbon isotope abundance, molecular mass spectra, and biochemical concentrations, especially amino acids, is of very high value in understanding the biotic potential of an environment and in assessing probability of life. The mass spectrometer can do these jobs and more, and mass spectrometers can be augmented by chromatographic input systems, but in-situ mass spectrometry in these situations has never been accomplished, although the mass spectrometer itself is well understood. Thus, sensors of advanced sophistication are the highest risk of the list, but their value justifies their inclusion. We note that to incorporate sensors such as mass spectrometers, one must address very challenging general issues of microfluidics and sample selection and handling in high ambient pressures. This is an area in which Earth-site experience is essential to considering a planetary deployment.

10. THE FUTURE OF IN-SITU AND SUBSURFACE EXPLORATIONS IN THE SOLAR SYSTEM

Europa is not alone, of course, in having scientific interest in a subsurface that may have or have had liquid water. In the course of pursuing the study of the solar system, NASA has found other icy sites, and clearly there are water and ice sites on Earth in which there are scientific questions of significance. In past NASA was largely a remote sensing organization, and a great deal was learned, and is still being learned, from remote sensing about Earth as well as planetary and astronomical bodies. Today, there is strong interest in extending that information through in-situ exploration, and there is a vast array of new microinstruments to enable in-situ analytical measurements of remarkable sophistication. This measurement technology comes from marine science and technology, the space program, the medical device industry, the communications industry, the military, and other areas, and it is in the process of changing much of how we measure and monitor processes of all sorts. In the space program in-situ operationsl have occurred on the moon and Mars

11. MARINE TECHNOLOGY DEVELOPMENT

Many elements of the Europa Ocean probe's design may be drawn from existing technology used in today's marine industry. Brushless motors and certain types of electronic circuitry, pressure-compensated in oil or other inert fluids to ambient pressure, have proven their reliability at full-ocean depth. Acoustic telemetry and navigation systems can easily manage data rates of 1 Kb/sec or better at ranges in excess of 1 km. In autonomous underwater vehicle (AUV) systems, where real-time communication with the surface often is impossible, onboard microprocessors give the vehicles sufficient intelligence to perform preprogrammed surveys and other simple activities, and to react to unexpected occurrences with evasive maneuvers and self-rescue routines. Strong, lightweight, and corrosion-resistant materials are widely used in oceanographic applications with long-term exposure to the marine environment and to full ocean depth.

The motivation to miniaturize the probe, particularly its outside diameter, comes from both the space segment constraints of mass and volume and the need to reduce the time and energy required for it to transit through the ice layer to the liquid water below. In prior experiments conducted by the Polar Ice Coring Office (PICO) at University of Nebraska in Lincoln, it was found that melting a hole for a 127 mm OD probe 3 m in length required almost 5 kW to travel a bit less than 2m/hr in approximately 20 C ice. Miniaturization, then, is a driving factor in all aspects of the probe design.

If the probe is to have sufficient mobility to explore the ice/water interface, the bottom sediment, and the body of water itself, it must be equipped with some form of buoyancy control, as well as propulsion. Some or all of the probe's in-water weight may be offset with fixed-displacement flotation. Thrusters or variable ballast systems may be used to correct for remaining discrepancies between the probe's weight-to-displacement ratio and the density of water. Any improvements that can be made in the efficiency of the buoyancy material, as well as in reduction of the payload weight (from such items as thrusters, actuators, cameras, lights, sensors, power supply, and pressure-resistant housings) will result in a decrease of overall vehicle size. Thus, it is likely that the probe's construction will include such materials as advanced thermoplastics and composites in addition to high strength metal alloys.

By definition, any probe intended for exploration must have sufficient flexibility to cope with the unexpected, and this will certainly apply to the Europa subsurface vehicles. Areas of concern include water density, visibility, and corrosiveness. A mismatch in water density could render the vehicle immobile if its thrusters and variable ballast systems cannot overcome the error. Visual imaging is key for line-of-sight navigation and subjective evaluation of unknown environments, and any means of improving the range and effectiveness of video camera and lighting systems in turbid water should be incorporated on the probe. Finally, the probe should be tolerant of corrosive chemicals, and probably of radiation exposure as well. Many plastics are problematic as they become brittle with exposure to radiation, halogenated polymers (PTFE, PVdF, PVC) release halogen acid vapor, and sulfur dioxide is released from polysulphone plastics. Silicon carbide and related ceramics are a possible solution. This is a research topic with insufficient guidance at this time.

As mentioned earlier, the method of communicating through the ice without a tether might be solved by releasing wireless transceivers in the ice every few hundred meters. Once the vehicle is in the water, acoustics may be used to communicate at greater range, although maximum bandwidth and reliability will be affected by thermal and salinity gradients as well as ambient noise, and power is a concern with acoustics. In any case, some form of navigation will be needed to keep the probe within range of the communication link. This problem is compounded in strong tidal currents, which could overwhelm the probe's maneuvering capability. One simple solution would be to deploy an anchor in the ice a few hundred meters above the point the probe enters the water, and operate the probe as a mobile pendulum suspended on the end of a cable. A controllable cable reel attached to the ice anchor could regulate the depth of the probe under the ice. With reasonably trimmed buoyancy, the probe could propel itself upward to inspect the underside of the ice, or cast itself horizontally within the limits of its tether like a fishing lure. With a sufficiently long cable (and a heavy depressor weight to help punch through strong current layers), the probe could conceivably be lowered all the way to the ocean floor below.

If the probe is a free swimming AUV, it may be equipped with such navigation devices as acoustic transponders and inertial guidance systems to monitor its position with respect to the entry point. A docking station for base-to-surface communications and for housing analytical instruments that are too large for the probe could be permanently suspended in the water from an ice anchor. After each survey, the probe would home to the docking station using acoustic and optical targets, and download its collected samples and data.

The risk of losing a free swimming AUV prematurely can be reduced by simplifying its task load and increasing the numbers of vehicles. As Kevin Kelly wrote in his book, *Out of Control*, "it is the great irony of life that a mindless act repeated in sequence can only lead to greater depths of absurdity, while a mindless act performed in parallel by a swarm of individuals can, under the proper circumstances, lead to all that we find interesting". One can imagine a central base station suspended in the water, from which swarm hundreds of small AUVs with very simple missions, reporting back one-by-one when their task is completed. It would be relatively straightforward to change the task of the swarm by reprogramming each AUV when it returned to base.

One advantage of using a radiothermal power source over batteries or fuel cells is that ample long-term power is available. Power is a prime constraint in submersible design, and acoustic devices are power hungry. One alternative to maintaining continuous communication with the probe is to program it to descend through the ice, conduct a free-swimming excursion for a predetermined period, and then return to the surface of the ice to transmit its collected data. The wait for each new transmission would be nerve-wracking, as it could be months or years between each one. There is no guarantee that the position where the probe resurfaces would be suitable for radio transmission, and a heavy emphasis is placed on the ability of the probe itself to climb back to the surface, navigating around obstacles along the way. All of these issues work against the notion of system miniaturization and simplilcity.

The lesson we in the oceanographic industry have learned time and again is that simple solutions work best. Highly complex systems can be made to function in reasonably benign environments, but in the harsh oceans, where corrosion, conductivity, and pressure wreak havoc, particularly on electronics, most state-of-the-art technology has little chance of surviving. The key to developing a successful technology for exploring Europa and other remote water-containing environments is to construct it as an assembly of simple, well-tested components, and to include many layers of redundancy. This technology may have a semblance of complexity, and may be able to achieve remarkable results, but it will also have the core of simplicity necessary for reliable operation in the ocean.

12. THE PROGRAMMATIC ROAD TO EUROPA'S OCEAN

We note that Europa once had and probably now still has an ocean; that the ocean is deep, salty, and cold; and that its characteristics are not known--we do not know if it is at all like our ocean. We put forward that this discovery will significantly alter our sense of place. If our ocean is the key to the development and maintenance of life on Earth, the ocean on Europa may play a similar role. If there is life on Europa it will significantly change how we see life on Earth. We need to explore this moon of Jupiter, and it is within our capabilities to do so. We understand the technical issues we need to address to accomplish this exploration, even if we don't have solutions for all of them. What are the next steps?

In the current way of doing space exploration in the United States, NASA is central to all missions. This may change; commercial deep space missions are being examined, but for today, NASA has to do the real work. That is not bad news. NASA is a large, capable agency; it has carefully thought-through strategies for planning; and it has an array of advisory committees of very bright experts. NASA also has mass and momentum, and this means that a new concept such as exploration of an extraterrestrial ocean must build its presence over time. In effect the trip to Europa's ocean will happen, but at this time we do not know when.

The approach that NASA has taken to planetary exploration usually involves incremental steps in which high risk technologies are tested on less ambitious missions before later use on a more ambitious mission. The Europa Orbiter is planned for launch in 2003, and should that mission confirm the Europa ocean, a follow-on mission to explore the ocean would inevitably be conducted. (In fact, given the information now on hand, a deep sub-surface mission to Europa makes emminent sense, even if we cannnot prove that the liquid ocean is still there.) The key mission - the Europa Ocean Observatory - would likely include a small tethered submersible for observations in the near vicinity of the station. The oceanic exploration can probably be conducted with a plausible extrapolation of current technologies without radical innovations. A more ambitious mission involving an excursion to the bottom of the ocean, would require breakthroughs in many technologies as described above. NASA is formulating a vision for understanding the origin of life in the solar system and in the galaxy, and the Europa Ocean Observatory is a key element in implementing that vision.

13. IN CONCLUSION: LET'S GET STARTED

We have laid out a technology development concept that will result in an instrumented probe collecting data in the Europa ocean in the second decade of the century and will, in the process, provide significant new technology for marine applications on Earth. These technologies will come in the areas of miniaturization, autonomy, instrumentation, materials and communications. As it has in other areas, the space program can generate significant spin-off developments for the academic and private sectors, if the program can involve the very capable marine research, development, and operations expertise available. The Europa Ocean Observatory mission is a grand challenge for us and a priceless inheritance for our chidren; NASA, when can we get rolling?

REFERENCES

Abyzov, S., I. Mitskevich, M. Poglazova, 1998, Microflora of the deep glacier horizons of Central Antarctica, *Microbiology 67*, 451-458.

Anderson, J., E. Lau, W. Sjogren, G. Schubert, W. Moore, 1998, Europa's differentiated internal structure: Inferences from two Galileo encounters, *Science 276*, 1236-1241.

Drinkwater, M., LIMEX'87 ice surface characteristics: Implications for C-band SAR backscatter signatures, *IEEE Trans Geosci. and Remote Sens., 27*, 501-513, 1989.

Gaidos, E., K. Nealson, and J. Kirschvink, 1999, Life in ice-covered oceans, *Science, 284,* 1631-1633.

Hoffman, P., A. Kaufman, G. Halverson, and D. Schrag, A neoproterozoic snowball Earth, *Science 281*, 342-346, 1998.

Hoppa, G., B. Tufts, R. Greenberg, and P. Geissler, Formation of cycloidal features on Europa, *Science, 285*, 1899-1902, 1999.

Khurana, K., M. Kivelson, D. Stevenson, G. Schubert, C. Russell, R. Walker, and C. Polanskey, Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto, *Nature 395*, 777-780, 1998.

McCord, T., G. Hansen, F. Fanale, R. Carlson, D. Matson, T. Johnson, W. Smythe, J. Crowley, P. Martin, A. Ocampo, C. Hibbits, J. Granahan, 1998, Salts on Europa's surface detected by Galileo's Near Infrared Mapping Spectrometer, *Science 280*, 1242-1245.

Nealson, Kenneth, Sediment Bacteria: Who's there, what are they doing, and what's new?, *Annu. Rev. Earth Planet. Sci. 25*, 403-434, 1997

Sassen, R., S. Joye, S. Sweet, D. Defreit, A. Milkov, and I. Macdonald, Thermogenic gas hydrates and hydrocarbon gases in complex chemosynthetic communities, Gulf of Mexico continental slope, *Organic Geochemistry*, in press.

Sharp, M., J. Parkes, B. Cragg, I. Fairchild, H. Lamb, and M. Tranter, Widespread bacterial populations at Glacier beds and their relationship to rock weathering and carbon cycling, *Geology, v27*, 107-110, Feb., 1999.

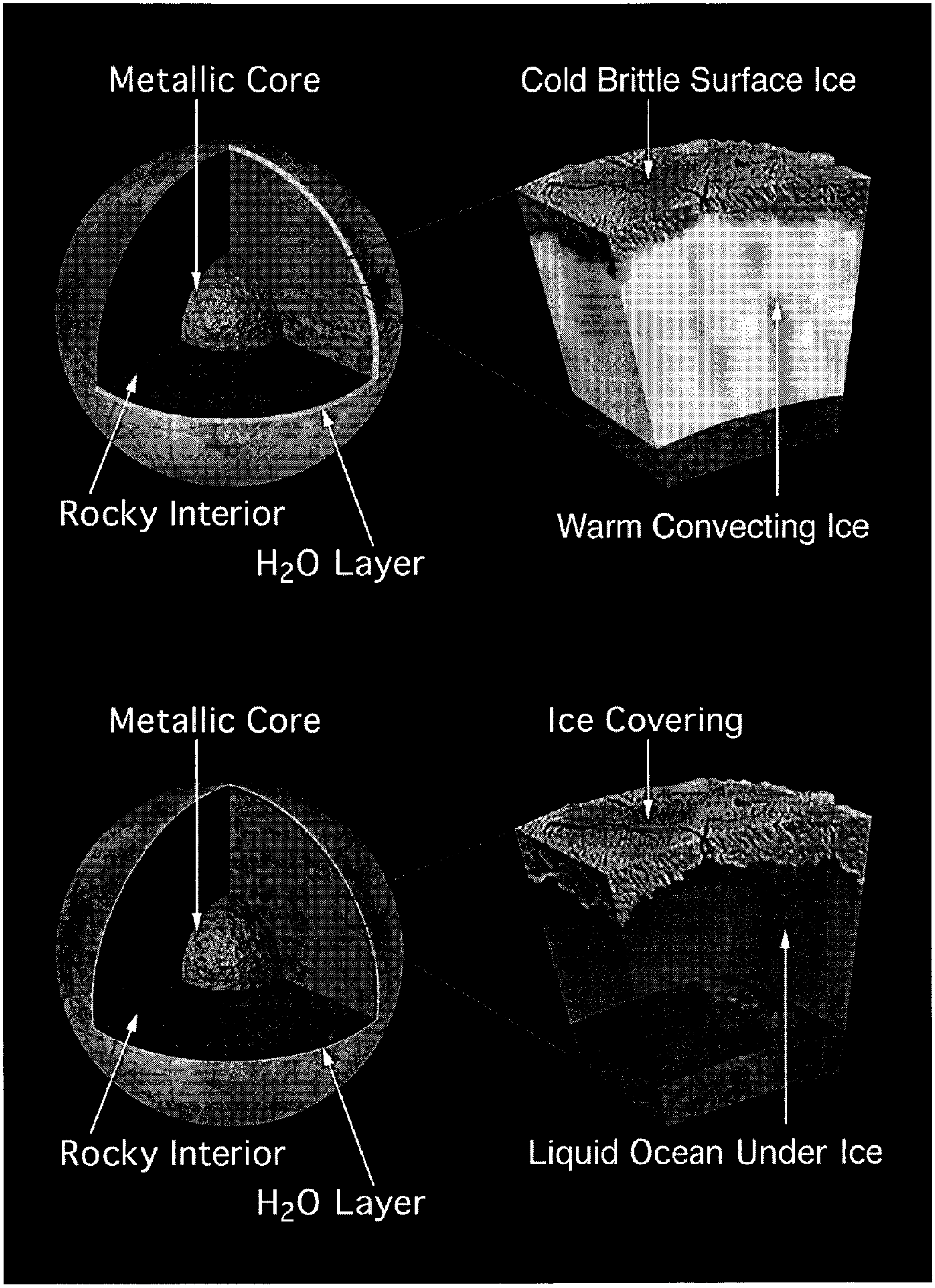
Swithinbank, C., *Satellite image atlas of glaciers of the World: Antarctica*, p B98, USGS Prof. Paper 1386-b, US Govt Printing Office, washington DC, 278 p, 1988.

Uchida, T., P. Duval, V. Lipenkov, T. Hondoh, S. Mae and H. Shoji, Brittle zone and air-hydrate formation in polar ice sheets, *Mem Natl Inst Polar Res, 49*, 298-305, 1994.

Figure 1. Models of Europa's interior based on data from Galileo. Image data supports both models, suggesting that there may be a thin brittle ice surface underlain by a warmer ice layer, which undergoes solid-state convection, and the ice is underlain in turn by a deep ocean.

Figure 2. An image of the Europa surface (See this image and more at http://www.jpl.nasa.gov/galileo/images.html). The "floes" visible here are a few kilometers across and bear striking resemblance to sea ice floes or cakes floating in a brash ice field which one might see in the Labrador Sea (Drinkwater, 1989) or to fragments of Antarctic ice shelves seen in Landsat images (Swithinbank, 1988).

Figure 3. Sterilization and cleanliness requirements anticipated for future planetary missions to habitable sites, of which the Europa ocean is a prime example. Note that even dead microbes are unwelcome on space missions of the future. The vertical axis calibration is not to be read exactly; these are approximate numbers extrapolated from discussions involving NASA management and the scientific community.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Metallic Core
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H_2O Layer
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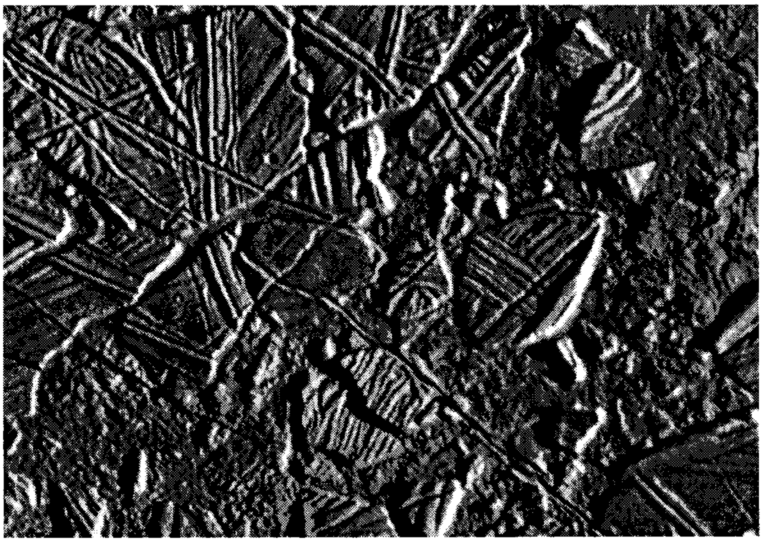

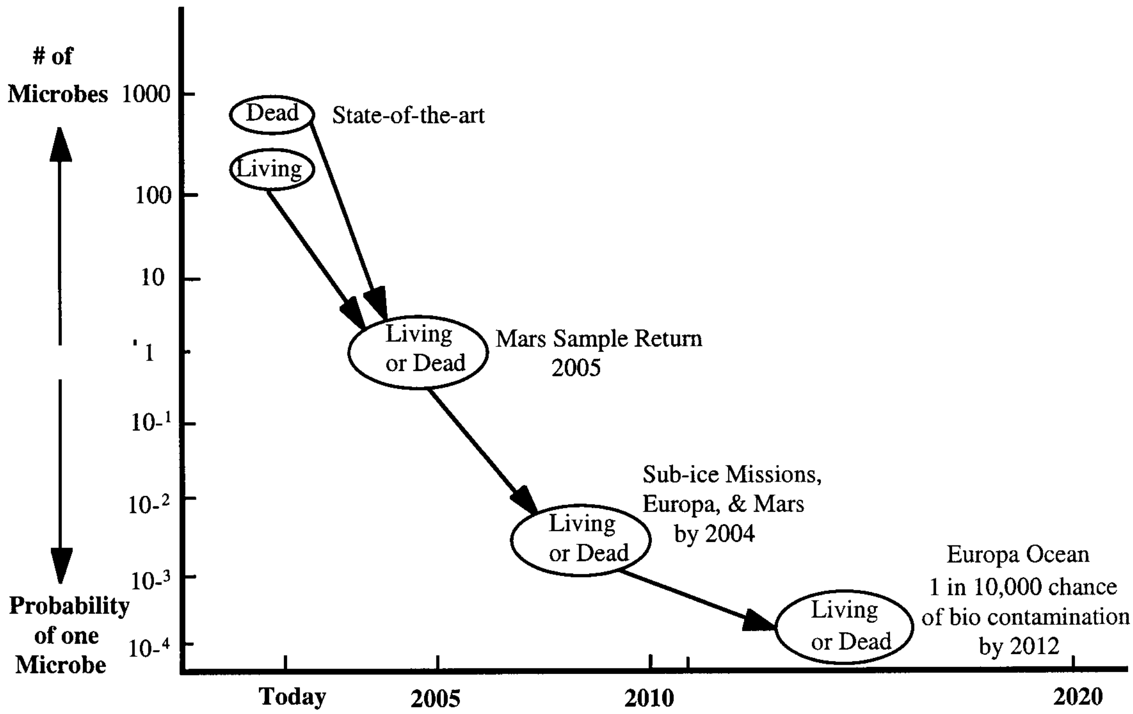

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of bio contamination
by 2012
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